Title: The quantum world: from weird to wired

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Abstract: Does quantum mechanics really tell us that particles, molecules, and maybe even cats, can be in two places at once? Does it force us to deny a reality that is independent of our observation? How can scientists disagree about what quantum mechanics means and yet still agree that it is right? Joseph Emerson, co-writer of the award-winning documentary â€œThe Quantum Tamersâ€•, will address these questions and then describe, drawing on preview clips from the documentary, how the weirdness of the quantum world is now being harnessed for a â€˜quantum information revolutionâ€™ that includes quantum teleportation, super-secure quantum communication, and the exponential power of quantum computation.

THE QUANTUM WORLD

from Weird to Wired!

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QUANTUM MECHANICS

"I think I can safely say that nobody understands quantum mechanics."

- Richard Feynman

Nobel Laureate in physics (1965)

WHAT IS QUANTUM MECHANICS?

The theory of quantum mechanics was developed to describe atomic and molecular systems, for which it has made predictions of unprecedented accuracy.

Quantum theory is responsible for technologies of huge social relevance, such as the laser, the transistor, medical imaging devices, superconductivity, and nuclear power ...

WHAT IS QUANTUM MECHANICS?

As a result quantum mechanics is probably the most *successful* and *important* physical theory ever devised by humanity...

but ...

QUANTUM MECHANICS IS "SHOCKING"?

"Anyone who is not shocked by quantum mechanics has not understood it."

- Neils Bohr

Nobel Laureate in Physics (1922)

WHAT IS WEIRD ABOUT QUANTUM MECHANICS?

Once the founders developed a full theory of quantum mechanics, it was immediately clear that the theory had very unusual features:

- Wave-Particle Duality.
- Inherent Uncertainty and Fundamental Limits to Description and Prediction.
- The Mystery of Quantum Superposition
- Entanglement and Spooky Action at Distance.

This evening I will describe the above phenomena and explain how they are relevant to the new field of quantum information science.

WAVE-PARTICLE DUALITY

The central mathematical object of the theory is a *wave*, and the central equation is a *wave-equation*, called the *Schrodinger equation*.

As a result, one can perform experiments where particles behave like waves.

This is *wave-particle duality*.

DOUBLE-SLIT EXPERIMENT

The wave-like properties of quantum particles leads to the curious phenomena of ***quantum interference***.

The ***wave-particle duality***, and resulting interference, is best illustrated through what is known as the ***double-slit experiment***...

DOUBLE-SLIT EXPERIMENT

So particles behave like waves… but only when we don't look? … Huh?!?

…Think of how a souffle can collapse when you open the oven to check on it!

In quantum mechanics, the ***act of observation*** plays a crucial role and must always be taken into account.

In particular, the wave-like property of particles, which leads to "***quantum coherence***", is destroyed by the act of observation - this process is called "***decoherence***".

QUANTUM COHERENCE IS FRAGILE

For the double-slit experiment, this means that if we *observe* which slit the particle passes through, by shining light on it, then the particle behaves like a particle, instead of a wave.

Quantum coherence properties are "fragile".

This is the main reason why building a quantum computer is a difficult thing.

FURTHER LIMITS TO OBSERVATION

Furthermore, according to quantum mechanics, even when we do measure/observe an object, we are unable to measure all the properties of an object *simultaneously*.

This is the *Heisenberg uncertainty principle*.

HEISENBERG UNCERTAINTY PRINCIPLE

Part of the explanation for this principle is the fact, taught to us by quantum theory, that light, which is the best tool for observation, is itself a particle.

This means that the light "particles" will ***physically disturb*** the object under observation... that is, when they bounce off of the object and into reflect into your eye.

FUNDAMENTAL LIMIT TO DESCRIPTION

For example, we can ***not*** measure the ***position*** and ***velocity*** of an object ***simultaneously***.

The fact that measuring one property, such as position, necessarily disturbs another property, such as the velocity, places a ***fundamental limit*** on how accurately we can ***measure*** and ***predict*** the properties of physical objects.

QUANTUM VS CLASSICAL PICTURES

Contrast this with classical "Newtonian" physics, where the properties of physical objects can always be measured *without disturbance*.

In our everyday experience, the fundamental limitation due to the Heisenberg uncertainty principle *is so small* as to be *negligible*.

QUANTUM VS CLASSICAL PICTURES

So, due to the uncertainty principle, properties such as the position and velocity of baseballs, planets and cars *only seem* to be measurable *simultaneously* to arbitrary accuracy.

Because our world is *quantum*, *in principle and in practice*, such perfectly precise measurements can't actually be done!

This is good news! It means that I do not have to pay the photo-radar speeding ticket I got in Quebec last month! Doesn't it?

MY SPEEDING TICKET

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TRANSLATION
STATEMENT OF OFFENCE

No : [redacted]

CANADA
PROVINCE OF QUEBEC
Judicial district of BEAUHARNOIS

No [redacted]

DEFENDANT [redacted]

[redacted]

PROSECUTOR
Directeur des poursuites criminelles et pénales
1200, route de l'Église, 3e étage
Québec (Québec)
G1V 4M1

REPR. ORG. [redacted]
Mandator No. :
[redacted]
File no. : [redacted]

plate number : [redacted]

I have reasonable grounds to believe that the defendant has committed the following offence, on or around 2010-02-13 at 17:01 à Pincourt, à 350 m à l'ouest du boulevard de l'Île sur l'autoroute 20 Est

!

drove at a speed of 90 km/h, where the speed limit indicated on the traffic signs erected under this section, the second paragraph of section 628 or section 628.1, was 70 km/h.

Highway Safety Code (R.S.Q., c. C-24.2), section(s) 329, 332, 516.1, 592.1 and 516.

SO SHOULD I PLEAD NOT GUILTY?

Dear Ministere de la Justice du Quebec, March 3, 2010

I hereby plead *not guilty* to photo-radar traffic ticket no. XXXXX because the stated offence, ***as described in the citation***, violates the fundamental laws of physics, in particular, the ***Heisenberg uncertainty principle***.

I submit, as evidence, my course notes for **Applied Math 473**, **Advanced Quantum Theory**, in which the above principle is derived from the axioms of quantum mechanics.

Sincerely,

Joseph Emerson
Quantum Mechanic
University of Waterloo

TECHNICALLY...

From the physics point of view, the citation could have said:

"... 350 m +/- 0.00000001 m ...
... 90 km/h +/- 0.00000001 km/h ..."

and then their claim would safely meet the minimum set by the Heisenberg limit!

REST ASSURED…

Maybe lawyers don't know as many quantum mechanical technicalities as they should…

While I am sure people have "gotten off" on "flimsier" technicalities…

… I am happy to pay my debt to society and be done with it!

MEANWHILE, ARE YOU SHOCKED YET?

- Particles exhibit quantum coherence *only when* we don't look at them.

- Further, quantum theory leaves some properties undefined, and tells us that we can not even go and measure all properties simultaneously.

So, what's really going on *when we are not looking*?

This is the central question for the *interpretation of quantum mechanics*. Here is one answer...

TRUE MEANING OF COHERENT SUPERPOSITION?

This is probably the most common view - that the literal interpretation meaning of quantum superposition is that particles can and do ***exist in two places at once***.

The most famous expression of the bizarre consequences of this point of view is given by the story of Schrodinger's cat...

SCHRODINGER'S POINT

"One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny amount of radioactive substance, so small, that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; ..."

- Erwin Schrodinger (1935)

HOW DO WE MAKE SENSE OF ALL THIS?

The main founders of quantum mechanics, Albert Einstein, Neils Bohr, and Erwin Schrodinger (who all won Nobel prizes for their work on quantum theory), could never quite agree on what quantum mechanics ***actually*** tells us about the nature of reality.

The debate between Einstein, Bohr, Schrodinger and others spanned their entire lives…

… and these issues are still debated even today!

See: http://www.iqc.ca/activities/courses/
Foundations and Interpretation of Quantum Theory

QUANTUM PICKLING

<u>Recipe for Crisp Pickles:</u>

1. Pack pickles in salt and ice overnight.
2. Cut 1/8 inch off blossom end.
3. Cold pack veggies in jar.
4. Add boiling brine solution: 1-1 ratio vinegar to water, 1 tbsp. salt, 1 tbsp. sugar.
5. Process minimum time according to altitude chart.

Which step makes them crisp and why?

A PLETHORA OF VIEWS

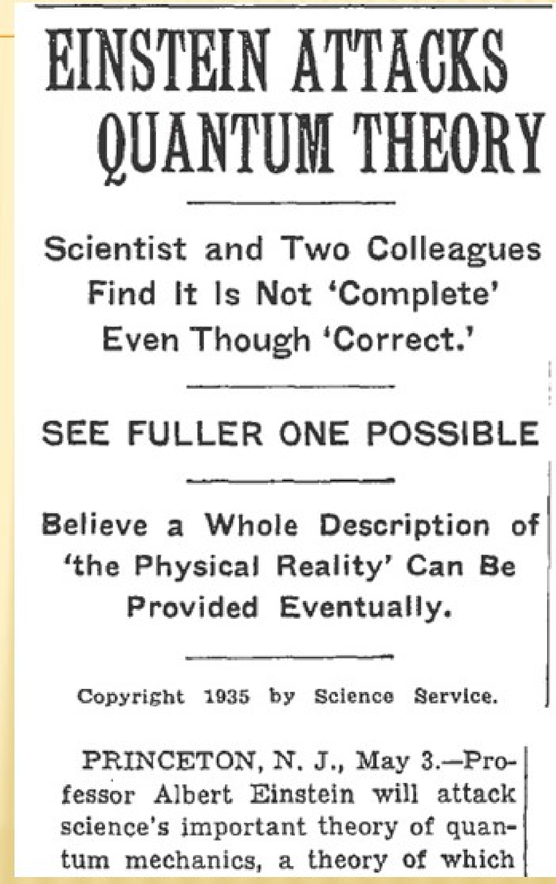
Bohr's view was that quantum theory is the ***final story***, and Nature just does not assign definite properties that are independent of our observation.

Einstein's view was that quantum theory gave an ***incomplete picture of reality*** – and we need to work hard to find a deeper theory that is more "reasonable".

Modern views include the infamous "***many-worlds***" interpretation, the ***deBroglie-Bohm pilot-wave theory***, which assigns an ***objective reality***, and many others.

THE "EPR" ARGUMENT

In an effort to prove his view correct, Einstein, along with Rosen and Podolsky, showed that a ***special class*** of quantum states implied a "***spooky action at a distance***"... <u>if</u> we accepted that quantum theory was indeed the final picture of reality.



EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

Copyright 1935 by Science Service.

PRINCETON, N. J., May 3.—Professor Albert Einstein will attack science's important theory of quantum mechanics, a theory of which

New York Times (1935)

SPOOKY ACTION AT A DISTANCE

Debates about interpretation have practical consequences!

The class of states EPR considered, called ***entangled states***, are now understood to be central to the benefits of quantum information.

Indeed, some 30 years after EPR, the genius of **John Bell** was to show that entangled states exhibit "spooky action at distance" that can be measured experimentally, ***no matter what you choose as your interpretation of quantum theory***.

TRANSITION: QUANTUM INFORMATION

With the weirdness of quantum mechanics experimentally confirmed, and the dawn of the information looming, physicists starting wondering about the practical consequences of quantum weirdness for communication and computation!

This is the "weirdness" getting "wired".

Here one of the key insights was from physicist Richard Feynman.

POWER OF QUANTUM COMPUTATION

So it turns out the answer is that quantum information is very useful.

Quantum computation, which makes uses of quantum effects, such as coherent superpositions, leads to algorithms that are *exponentially more efficient* than their best classical counterparts.

This "exponential" separation means the *practical feasibility* of solving some problems that are *otherwise intractable.*

What kinds of algorithms?

FACTORING AND PRIVACY

The breakthrough that really put the idea of quantum information "on the map" was the discovery of Peter Shor that a quantum computer could factor large numbers easily.

What does this mean and why is it important?

I'll let Peter Shor tell you himself…

WHAT HAVE WE LEARNED?

I hope I have given you a sense of the unusual kind of world our quantum world is, and also conveyed some of the ways in which quantum mechanics has had, and continues to have, a profound impact on technology and society.

Remember, if you feel like you still do not understand quantum mechanics, you're in good company!

Thank you for your attention!